PARTICLE SIZE DISTRIBUTIONS OF GROUND CORN AND DDGS FROM DRY GRIND PROCESSING

K. D. Rausch, R. L. Belyea, M. R. Ellersieck, V. Singh, D. B. Johnston, M. E. Tumbleson

ABSTRACT. *Ethanol production has increased in the past decade as a result of growth in the dry grind industry. In the dry grind process, the first step is grinding of corn. The particle size of the resulting ground corn can affect the fermentation process and the particle size of dried distillers' grains with solubles (DDGS), a coproduct of dry grind processing. Few data are available that characterize particle size distributions of ground corn or DDGS. The objective was to determine particle size distributions of ground corn and DDGS. Samples of ground corn and DDGS were obtained from nine dry grind plants; particle size distribution, geometric mean diameter (d_{gw}) and geometric standard deviation (S_{gw}) were determined. The d_{gw} of ground corn and of DDGS were not different among processing plants. The overall mean d_{gw} of ground corn was not different from that of DDGS. Most of the ground corn (80 g/100 g) and DDGS (70 g/100 g) were recovered in the three largest particle size categories. The particle size distributions of ground corn were not correlated (r < 0.35) to particle size distributions of DDGS.*

Keywords. *Coproducts, Corn, DDGS, Distillers dried grains with solubles, Ethanol.*

Corn is processed into ethanol by one of two major processes: dry grinding or wet milling. Wet milling is more complex than dry grinding because fiber and germ components are separated; this requires considerable equipment and capital. In the dry grind process, corn is ground and fermented without separation of components. Dry grind requires less equipment and capital; dry grind plants produce relatively small volumes of ethanol, usually are producer owned, and contribute considerably to local economies.

In the dry grind method, the first step is to grind whole corn by passing it through a hammer mill containing screens with relatively small openings (3.2 to 4.8 mm diameter). The resulting ground corn consists of a mixture of particles of different sizes. Particle size distribution is affected by both equipment and corn characteristics. Grinding conditions, such as type of mill used, screen size, mill speed, and equipment condition, can affect particle size distribution (Henderson and Perry, 1976). Breakage susceptibility and hardness characteristics determine how corn kernels break apart; both are affected by hybrid, kernel moisture and density and other physical characteristics (Kirleis and Stroshine, 1990; Peplinski et al., 1989; Pomeranz et al., 1986; Wu, 1992).

The particle size distribution of ground corn can impact processing conditions, such as rate and extent of fermentation, particle size of solids in liquid streams, and separation of solid materials from liquid (Kelsall and Lyons, 2003; Maisch, 2003). Particle size distribution of ground corn could potentially affect particle size distribution of the resulting coproduct, distillers' dried grains with solubles (DDGS). Dry grind plant operators contend that particle size distribution of ground corn affects particle size distribution of DDGS, which impacts its handling characteristics and market value. There are no published data that describe particle size distributions of ground corn and DDGS from dry grind plants. The objective of this study was to measure particle size distributions of ground corn and DDGS and to determine the relationship of particle size of ground corn to that of DDGS.

MATERIALS AND METHODS

Nine dry grind ethanol plants located in the upper Midwest (Minnesota, Missouri, and South Dakota) participated in the study. They processed commodity yellow dent corn purchased from producers in the surrounding region. In each plant, corn was ground with a hammer mill equipped with a screen. Diameters of screen openings varied from plant to plant and ranged from 3.2 to 4.8 mm; screens and hammer mills were maintained according to individual plant operating practices. It took approximately 20 h to grind sufficient corn to fill a fermentation tank, and subsamples of ground corn (approx. 1 kg each) were taken every 4 h during grinding. Thus, five subsamples initially were taken and eventually combined to form one composite sample used for measurement of particle size distribution. Samples of ground corn were obtained from each plant during each of three weeks (one sample per week) during each of two collection periods, resulting in 54 samples of ground corn.

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The authors are **Kent D. Rausch, ASAE Member Engineer,** Assistant Professor, **Vijay Singh, ASAE Member Engineer,** Assistant Professor, and **Mike E. Tumbleson,** Professor, Department of Agricultural and Biological Engineering, University of Illinois at Urbana−Champaign, Urbana, Illinois; **Ronald L. Belyea,** Professor, Department of Animal Sciences, and **Mark R. Ellersieck,** Professor, Department of Mathematics and Statistics, University of Missouri, Columbia, Missouri; and **David B. Johnston,** Food Technologist, USDA−ARS Eastern Regional Research Center, Wyndmoor, Pennsylvania. **Corresponding author:** Kent D. Rausch, Department of Agricultural and Biological Engineering, University of Illinois at Urbana−Champaign, 1304 W. Pennsylvania Ave., Urbana, IL 61801; phone: 217−265−0697; fax: 217−244−0323; e−mail: krausch@uiuc.edu.

Samples of DDGS were obtained during the same collection periods during which ground corn was sampled, resulting in 54 DDGS samples. Since fermentation is a batch process, sampling was sequenced so that ground corn samples and DDGS samples were from the same initial batch of whole corn. DDGS samples were taken from a sampling port that randomly sampled the DDGS as it was being transported via conveyer to storage facilities but before it was blended with DDGS from other batches.

Particle size distribution was measured using a sieve shaker (model RX−86, W. S. Tyler, Mentor, Ohio) equipped with six sieves (U.S. standard sieve Nos. 10, 20, 30, 40, 45, and 60) and a pan. The sieve sizes determined the particle size categories, which are reported in g per 100 g retained on the smaller screen: 2.0 mm and larger (2.0 mm), 0.84 to 2.0 mm (0.84 mm), 0.60 to 0.84 mm (0.60 mm), 0.43 to 0.60 mm (0.43 mm), 0.35 to 0.43 mm (0.35 mm), 0.25 to 0.35 mm (0.25 mm), and less than 0.25 mm, respectively. The sieving procedure was similar to that described in *ASAE Standards* (1995), with modifications. The procedure originally called for 100 g of ground corn and 10 min sieving time. These conditions resulted in low repeatabilities due to clumping of ground corn on sieves with smaller openings. After considerable testing, we found that drying ground corn overnight at 55°C, reducing sieving sample size to 60 g, and increasing sieve time to 30 min improved repeatability. Therefore, all ground corn samples were dried overnight before sieving, and a sample size of 60 g and a 30 min sieving time were used. DDGS samples were not dried prior to sieving, but 60 g samples and 30 min sieving times were used. Sieve tests were done in duplicate. Geometric mean diameter (d_{gw}) and geometric standard deviations (S_{gw}) were calculated for each sieving replicate based on the procedure described in *ASAE Standards* (1995).

Effects of plant and period on d_{gw} of ground corn and d_{gw} of DDGS were determined using a general linear model of SAS (1985). Data were analyzed as a 2 × 2 factorial for effects of plant, period, and plant × period. Means were separated (using least squares means comparison) when effects were significant. Simple linear regression was used to determine the relationship between particle size of ground corn and particle size of DDGS (SAS, 1985). A random effects analysis of variance procedure (NESTED; SAS, 1985) was used to partition the variance associated with particle size distributions of ground corn and DDGS into plant, period, and error terms.

Results and Discussion

There were no significant effects of plant, period, or plant × period on d_{gw} of ground corn or of DDGS (table 1). There was variation in d_{gw} of both ground corn and DDGS. Variation in d_{gw} was greater for DDGS (0.83 to 1.00) than for ground corn (0.89 to 1.03). Mean d_{gw} for corn (0.94 mm) was not significantly different from mean d_{gw} for DDGS (0.92 mm). The S_{gw} dataset was large and is therefore not presented. However, the range in S_{gw} was 1.04 to 1.20 for ground corn and 1.07 to 1.39 for DDGS.

Geometric mean diameter is an effective means of expressing and comparing particle size distribution on a statistical basis. However, it is not a measure that is easily understood and applied by processors. The proportion of material recovered in each particle size category (g/100 g of sample) is a more useful and practical expression of particle size for processors. Particle size distributions (g/100 g sample) of ground corn and DDGS are presented in figure 1 as means across plants, periods, and weeks. Data in this figure show that for ground corn, there was somewhat more material on the larger screens than for DDGS, although differences were not large. For ground corn and DDGS, about 75% to 80% of the material was recovered in the 0.60 mm category or larger. These data suggest that the ground corn processed by these ethanol plants was relatively coarse. Particle size of the corn theoretically could be reduced considerably. This would increase the surface area to volume ratio of ground corn and could increase rates and/or extent of liquefaction, saccharification, and fermentation (Kelsall and Lyons, 2003). While these changes could improve processing efficiency, plant operators are hesitant to grind corn more finely because to do so increases energy demands for processing and (presumably) decreases particle size of DDGS. Reduced particle size of DDGS is thought to result in less desirable handling characteristics and to adversely impact digestion in ruminants.

The data in figure 1 are means pooled across plants and periods to provide a general overview of particle size data. Effects of plant on particle size distribution of ground corn were determined to provide information about the particle size distribution within each plant (table 2). There were

Table 1. Geometric mean diameter (d_{gw}) and geometric standard deviation (S_{gw}) for ground corn and DDGS by plant.[a]

Plant	Ground Corn d_{gw} (mm)	DDGS d_{gw} (mm)
1	0.89	0.83
2	0.93	0.96
3	1.03	1.00
4	0.91	0.93
5	0.99	0.88
6	0.90	0.95
7	0.92	0.92
8	0.94	0.86
9	0.94	0.86
Mean	0.94	0.92
SE	0.036	0.028

[a] Means did not differ (P < 0.05).

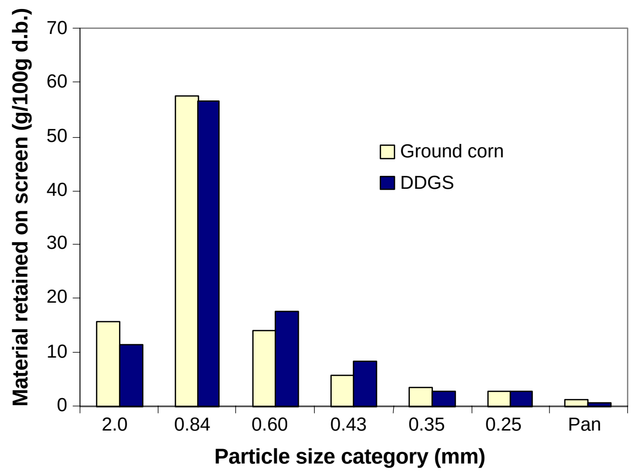

Figure 1. Mean particle size categories of ground corn and DDGS.

Table 2. Comparison of particle size distributions and d_{gw} for ground corn among dry grind plants.

Plant	Particle Size Category (retained on screen, g/100 g)[a]							d_{gw}[b] (mm)
	2.0 mm	0.84 mm	0.60 mm	0.43 mm	0.35 mm	0.25 mm	<0.25 mm	
1	18.6	47.7	16.5	6.9	4.7	3.8	2.4	0.89
2	14.5	57.2	15.2	5.0	3.8	2.9	1.1	0.93
3	10.4	68.4	10.0	4.7	2.9	2.6	1.0	1.03
4	16.0	55.9	15.0	5.3	3.4	2.9	1.0	0.91
5	12.1	63.0	11.9	5.7	3.4	2.8	1.2	0.99
6	17.4	55.4	15.4	4.5	3.4	2.7	1.3	0.90
7	26.8	47.7	13.6	5.3	3.4	2.2	1.0	0.94
8	23.0	48.9	14.9	6.5	3.7	2.2	0.9	0.92
9	18.5	59.0	12.1	4.0	2.9	2.3	1.2	0.91
Mean	11.5	56.5	17.5	8.3	2.7	2.8	0.7	0.94

[a] Particle size categories: SE = 1.83; LSD = 6.47; $P < 0.05$.
[b] No differences detected ($P < 0.05$).

Table 3. Comparison of particle size distributions and d_{gw} for DDGS among dry grind plants.

Plant	Particle Size Category (retained on screen, g/100 g)[a]							d_{gw} (mm)[b]
	2.0 mm	0.84 mm	0.60 mm	0.43 mm	0.35 mm	0.25 mm	<0.25 mm	
1	13.1	50.8	14.6	9.0	4.7	6.2	1.6	0.85
2	6.9	58.6	22.3	8.8	2.1	1.2	0.1	0.96
3	19.2	51.6	17.1	7.8	2.5	1.6	0.2	1.00
4	2.8	53.2	23.8	12.2	3.6	3.6	0.7	0.93
5	9.7	61.8	17.2	7.1	1.9	1.8	0.4	0.88
6	15.7	52.9	17.6	8.4	2.6	2.2	0.6	0.94
7	16.7	64.7	11.6	4.5	1.2	1.1	0.4	0.95
8	13.4	61.5	13.5	6.4	2.3	2.5	0.5	0.93
9	5.8	53.9	19.9	10.7	3.6	4.6	3.6	0.86
Mean	17.5	55.9	13.0	5.3	3.5	2.7	1.3	0.92

[a] Particle size categories: SE = 1.92; LSD = 6.38; $P < 0.05$.
[b] No differences detected ($P < 0.05$).

significant plant × particle size interactions. Within the two largest particle size categories, there were significant differences among plants. For example, in the 2.0 mm and greater category, plant 3 had the least material; in the 0.84 to 2.0 mm category, plant 3 had the most. The fourth category had less variation than the previous three, but there were some differences among plants. In general, the three smaller categories contained significantly less material than the four larger categories and were not different from each other.

For DDGS (table 3), there also were significant plant × particle size interactions. For example, within the largest category (2.0 mm and greater), plant 3 had the most material (19.2 g/100 g), whereas plants 2, 4, and 9 contained the least. In the second particle size category (0.84 to 2.0 mm), plants 5, 7, and 8 contained significantly more than the other plants. For the third particle size category, plants 2, 4, and 9 contained more material than the other plants. In general, as with ground corn, the three smallest categories had significantly less material that the four largest categories and were not different from each other.

These data show that the particle size distributions of both ground corn and DDGS can vary significantly among dry grind plants; the most variation was in the larger particle size categories. For example, plant 7 had 81.4 g/100 g of ground corn in the two largest particle size categories; most of the ground corn in this plant was 0.84 mm diameter or larger. Plant 4 had 56.0 g/100 g ground corn in these two categories. These differences are substantial, and although the effects on processing were not determined, they have the potential to affect certain parameters, such as fermentation time (Kelsall and Lyons, 2003).

Linear regression showed that the relationship between d_{gw} of DDGS and d_{gw} of ground corn was very weak (fig. 2); slope was small (0.0389), and R^2 value was low (0.0012). Correlation coefficients for relationships among individual particle size categories of ground corn and those of DDGS similarly showed that the association was weak (table 4). There were few significant correlation coefficients among the particle size categories of either material; all correlation coefficients were low ($r \leq 0.35$). These data clearly show that particle size of ground corn had little effect on particle size of DDGS.

There was considerable variation in d_{gw} of ground corn and DDGS among processing plants (table 1). Because

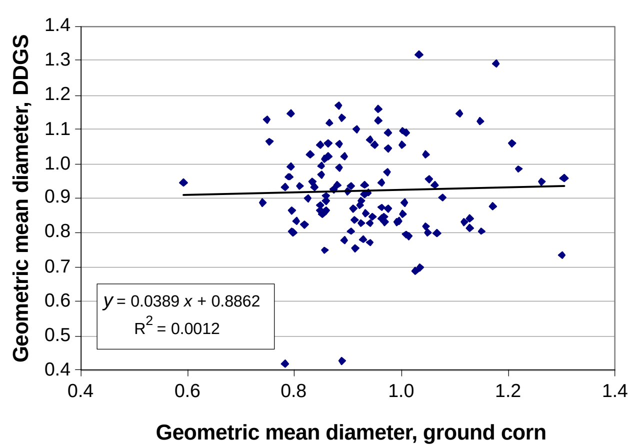

Figure 2. Geometric mean diameters (d_{gw}) of ground corn and DDGS.

Table 4. Correlations (r) between corn and DDGS particle size distributions (across plants and periods).

	Corn						
DDGS	2.0 mm	0.84 mm	0.60 mm	0.43 mm	0.35 mm	0.25 mm	<0.25 mm
2.0 mm	0.01	−0.10	0.14	−0.05	0.10	0.07	0.05
0.84 mm	0.11	−0.19	0.14	0.13	−0.07	−0.02	−0.00
0.60 mm	−0.16	0.35**	−0.28*	−0.07	−0.30**	−0.05	−0.11
0.43 mm	−0.07	0.21	−0.21	−0.05	−0.05	−0.05	−0.06
0.35 mm	−0.02	0.03	−0.06	−0.03	0.20	−0.10	0.02
0.25 mm	0.00	−0.12	−0.01	−0.02	0.23*	0.00	0.05
<0.25 mm	0.02	−0.07	0.06	−0.10	0.18	0.04	0.15

* = P < 0.10.
** = P < 0.05.

Table 5. Proportion (%) of variation attributed to plant and period effects on particle size distribution.

	Particle Size Category (retained on screen, g/100 g)						
Source	2.0 mm	0.84 mm	0.60 mm	0.43 mm	0.35 mm	0.25 mm	<0.25 mm
Ground corn							
Plants	13	41	1	4	9	8	11
Periods	26	26	6	20	9	0	3
Error	61	33	93	76	81	92	86
DDGS							
Plants	17	20	50	18	0	5	32
Periods	52	0	16	0	0	0	0
Error	31	80	74	81	100	95	68

particle size can affect processing efficiency, identifying sources of variation and minimizing particle size variation could suggest possible opportunities to improve processing efficiency. Partitioning of total variation using random effects analysis of variance showed that for both ground corn and DDGS, plants and periods accounted for some of the variation of some particle size categories (table 5). For example, for the two largest particle size categories of ground corn, plants and period accounted for 54% and 52% of variation, respectively. For the remaining particle size categories, plant and period accounted for 38% or less of variation. These data show much of the variation in most particle size categories was due to sources other than plant or period. Similar patterns existed for DDGS.

Some information is available on the effects of ground corn particle size on fermentation. Kelsall and Lyons (2003) suggested that 81 g/100 g sample of ground corn should be 0.43 mm or larger for efficient fermentation; they also suggested that not more than 11 g/100 g should be larger than about 0.84 mm and not more than 11 g/100 g be smaller than about 0.25 mm. These values for particle size categories are similar to those we found in the present study. Kelsall and Lyons (2003) reported that decreasing particle size of ground corn from a relatively coarse grind (0.80 mm) to fine grind (0.48 mm) increased ethanol yield from 0.366 to 0.396 L/kg. However, they suggested that decreasing the particle size excessively could have adverse affects on downstream processing steps, such as centrifugation. A concern that dry grind plant operators often express is that a reduction in the particle size of ground corn, even a small amount, significantly increases energy demand and cost. Guritno and Haque (1994) showed that reducing particle size of different grains significantly increased energy consumption. If reducing corn particle size improved processing efficiency, it may be possible to alter processing equipment to minimize energy utilization without decreasing DDGS quality.

Matthew et al. (1999) obtained samples of corn from different regions of the U.S. They found that extrusion properties of ground corn were affected by region of the country when grinding conditions were identical and that grinding condition (particle size) was an important factor in extrusion properties. Their data seem to corroborate our data; variation in corn properties could contribute to variation in particle size distributions among plants, which were located in different states (regions).

CONCLUSIONS

The d_{gw} of ground corn and DDGS were not different among processing plants or periods of sample collection; the mean d_{gw} for ground corn was not different from the mean d_{gw} for DDGS. Most of the ground corn (80 g/100 g) and DDGS (70 g/100 g) was found in the three largest particle size categories (larger than 0.60 mm openings). Correlations among particle size categories of ground corn and DDGS were very weak ($r \leq 0.35$). There was considerable variation among d_{gw} for both ground corn and DDGS; in general, plants and periods did not account for a very large portion of the variation.

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